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EFFECT OF SAND SIZES ON THE FLUIDIZATION BEHAVIOR IN CIRCULAR AND RECTANGULAR COLUMNS

ANWAR JOHARI[1] AND MOHD ROZAINEE TAIB[2]

Abstract. The effect of different sand sizes on the fluidization behavior in circular and rectangular columns was investigated. Three groups of sands with different mean diameters (Sand Sieve No. 10/20 (dp_{mean} = 0.870 mm), Sand Sieve No. 20/30 (dp_{mean}= 0.670 mm) and Sand Sieve No. 30/60 (dp_{mean}= 0.340 mm) were used. The experiment was conducted using circular and rectangular columns of same the cross-sectional area. The quality of fluidization was categorized into three flow regimes, namely laminar, turbulent and slugging flow. Results showed that large particle of group D (Sand Sieve No. 10/20) provided less resistance to the bed expansion due to its physical properties and the occurrence of slugs were more pronounced. Group D particles exhibited large bubbles compared to Group B particles of Sand Sieve No. 30/60. Particles of Group B showed good fluidization behavior. Fluidization quality was affected by the column size but it does not have any effect on the shape of columns being used.

Keywords: Sand sizes, Geldart's classification, Circular Columns, Rectangular Columns, Fluidization number

1.0 INTRODUCTION

Different sizes of sand particles exhibit different fluidization behavior. The measurements of physical properties of sand being used in the fluidized beds and the choice of sand size directly influence the hydrodynamics of the reactor column. The fluidization quality is closely related to the intrinsic properties of fluidizing medium. Properties such as particle density, particle size and surface characteristics definitely affect the outcome of the fluidization. Sand was chosen as a fluidizing medium due to its characteristics that can withstand high operating temperature of more than 1000^0C. Apart from that, its cheap cost and availability make it a preferred choice for the operation. Geldart classified powders into four different categories based on their density difference and mean particle size, namely Group C, A, B and D [1]. Group C was the smallest and most cohesive whilst Group D particle was the largest and demonstrated spoutable behavior. In dealing with particles with different sizes, particularly particles categorized by Gildart[1], several factors such as interparticle forces between particles and also certain mechanical strength such as elasticity as well as the hydrodynamic forces of the bed as pointed out by Rietema [2] on his review of Geldart's classification of powder. The adhesion force per particle contact depends on the surface geometry of the contacting particle and type of interaction

[1,2,3] Department of Chemical Engineering, Faculty of Chemical and Natural Resources Engineering, Universiti Teknologi Malaysia, 81310 UTM Skudai, Johor Bahru, Malaysia

forces between the particles [3]. However, inter-particle forces do not play any role in Group D particle due to their coarse size nature.

Slugging bed term was used to explain the nature of bed whereby fluidization, hence, mixing was very poor. Three types of slug flow were normally observed, namely wall slug, axi-symmetrical slug and solid slugs. It was believed that coarse particles gave rise to earlier slugging than smaller particles and this was attributed to the production of larger bubbles as stated by Geldart [4] and Hirio and Nonaka[5]. Mori and Wen [6] stated that the bubble diameter can be estimated by using correlation developed by Kobayashi and Arai [7]. The correlation incorporated the particle diameter in estimating the bubble diameter. Lu *et al.* investigated the mean bubble diameter using sand mean diameters ranges from 28.7 to 169 microns and found that the bubbles size increases with the particle size [8].

Group B particles fluidized well and bubbles started to form at or only slightly above minimum fluidization velocity. Bubble size was seen increased linearly with both bed height and excess gas velocity, $U\text{-}U_0$. The finding was supported by Horio and Nonaka [5]. They stated that bubbles formed in fine particles beds are smaller than those in large particle beds. Reviewed on the nature of each sand group also pointed out that group B more cohesive as a result of various forms of inter-particle forces

In order to determine the quality of the fluidization, the fluidization behavior of sand was characterized into three; laminar fluidization, turbulent fluidization and slugging regimes. The term turbulent fluidization was used to describe the nature of fluidization where the sand and the solid sample were all well mixed inside the bed. The solid sample was enable to penetrate into the bed bottom and moved back to the top of the bed. The circulation pattern of these two materials was observed throughout the tests. The turbulent fluidization was mainly observed when using high fluidization number. Laminar flow, on the other hand, was observed during low fluidizing number in which the circulation pattern was poor. Most of the solid sample stayed on top of the bed, unable to penetrate inside the bed bottom. In slugging flow, no mixing of solid sample and sand was observed and sand circulation pattern was very poor. Therefore, the main purpose of this study was to investigate the fluidization behavior of different mean sand sizes under selected operating conditions.

2.0 METHODOLOGY

Sands with different mean diameters (Sand Sieve No. 10/20, 20/30 and 30/60) obtained commercially were chosen in the hydrodynamics study. A simulated municipal solid waste with a diameter of 6 cm and about 100g was used as a sample. The sample comprised of four components, paper (19%), plastic (25%), food (27%) and vegetable waste (29%). The fluidization behavior was categorized into three different flow regimes and graded as shown in Table 1.

Table 1 Grading of fluidization behavior

Point	Fluidizing behavior	Observation
1	Slugging	Sample floated on top of the bed. Sand circulation very poor and no mixing between sand and sample
2	Laminar fluidization	Sample floated on top of the bed. Sand circulation very poor and no mixing between sand and sample. Slow moving bubbles
3	Turbulence fluidization	Sample well mixed inside the bed. Sand circulation very good and vigorous turbulent flow. Fast moving bubbles

Hydrodynamic studies of fluidized bed column were conducted using reactors with different shapes and sizes but all with the same area of fluidization. Three columns were constructed, a circular column and two rectangular columns. The shapes and sizes of the columns are shown in Table 2.

Table 2 Column shapes and sizes

Reactor type	Dimension	Area, m^2
Circular	21 cm diameter	0.0345
Rectangular – RC1	21 cm X 16.5 cm	0.0345
Rectangular – RC2	30 cm X 11.5 cm	0.0345

The sand height was fixed at 1 D_c, for circular column and 1 W for the rectangular columns. It should be noted that D_c stands for diameter of circular column and W for width of the rectangular columns. Prior to the commencement of the experimental study, the minimum fluidization velocity, U_{mf} was first determined for different sand sizes. Air was injected into the column via Galvanised Iron (GI) pipe, and the minimum fluidizing velocity for each mean sand size was observed through the first bubble occurred during the air injection. The minimum fluidizing velocity was calculated by dividing the airflow rate with the cross-sectional area of the circular column. The physical properties and its minimum fluidization velocity of the selected mean sand sizes is tabulated in Table 3

Table 3 Physical properties of sands and minimum fluidization velocity

Properties	Sand sieve No. 10/20	Sand Sieve No. 20/30	Sand sieve No. 30/60
Bulk Density (kg/m^3)	1460	1460	1340
Particle density (kg/m^3)	2440	2430	2330
Sphericity of sand, ϕ_s	0.87	0.9	0.84
Mean diameter of sand*, d_{sph} , mm	0.870	0.670	0.340
Bed voidage, ε	0.40	0.40	0.425
Minimum fluidization velocity, m/s	0.42	0.28	0.09

At a specified bed height, fluidization number was varied, ranges from 3 U_{mf} to 8 U_{mf}. The best operating conditions will be determined through visual observations.

3.0 RESULTS AND DISCUSSION

Three different sand mean diameters were used in the experiment namely sieve no. 30/60 (dp_{mean} = 0.34 mm), 20/30 (dp_{mean} = 0.67 mm) and 10/20 (dp_{mean} = 0.87 mm) respectively. Particles are classified into four different categories based on well accepted Geldart classification. Based on that classification, the sand sieve no. 30/60 used in the experiment can be included in Group B whereas sand sieve no. 20/30 and 10/20 were included in Group D. These three sand sizes exhibited different characteristics as they are categorized under different Geldart's particles grouping. Hence, their behavior was noticeably different during the conduct of experiments. Under this circumstance, group D particles (sand sieve no. 10/20 and 20/30) provided less resistance as the bed voidage is bigger (coarser material) than that of sand sieve no. 30/60 (Group B particle).

Results on the fluidization quality for three different shapes and sizes of reactor columns at different mean sand sizes are tabulated in Table 4, 5 and 6, respectively. The bed height was fixed at 1Dc for the circular column and 1W for rectangular column 1 (RC-1) and rectangular column 2 (RC-2). Note that 1Dc = 21 cm and 1 W for RC-1 and RC-2 were 16.5 cm and 11.5 cm, respectively. The total area for all reactor columns was fixed at 0.0345 m^2.

Table 4 Fluidization Quality for Sand Sieve No. 10/20 at different fluidization numbers for the tested reactor columns at 1 Dc and 1 W

Sand Sieve No.	**U_{mf}**	**Column Type**		
		Circular Column (21 cm diameter)	Rectangular Column (RC-1) (21 cm X 16.5 cm)	Rectangular Column (RC-2) (30 cm X 11.5 cm)
10/20	3	2	2	2
	4	2	2	2
	5	1	2	3
	6	*	2	3
	7	*	3	3
	8	*	3	3
	Total point	5	14	16

Note:
* experiment stopped due to the occurrence of slugging flow regime

Table 5 Fluidization quality for Sand Sieve No. 20/30 at different fluidization numbers for the tested reactor columns at 1 Dc and 1 W

Sand Sieve No.	**U_{mf}**	**Column Type**		
		Circular Column (21 cm diameter)	Rectangular Column (RC-1) (21 cm X 16.5 cm)	Rectangular Column (RC-2) (30 cm X 11.5 cm)
20/30	3	2	2	3
	4	3	2	3
	5	3	3	3
	6	3	3	3
	7	3	3	3
	8	1	3	3
	Total point	15	16	18

Table 6 Fluidization quality for Sand Sieve No. 30/60 at different fluidization numbers for the tested reactor columns at 1 Dc and 1 W

Sand Sieve No.	**U_{mf}**	**Column Type**		
		Circular Column (21 cm diameter)	Rectangular Column (RC-1) (21 cm X 16.5 cm)	Rectangular Column (RC-2) (30 cm X 11.5 cm)
30/60	3	2	3	3
	4	3	3	3
	5	3	3	3
	6	3	3	3
	7	3	3	3
	8	3	3	3
	Total point	17	18	18

Results show the increasing fluidization quality as pointed by the increase of grade point for all column types with respect to sand mean size. Generally, the Sand Sieve No. 10/20 exhibited poor fluidization quality with 16 points for rectangular column 2 (RC-2) and only 5 points for circular column. Rectangular column 1 (RC-1) accumulated 14 points. The quality of fluidization improved when using sand sieve no. 20/30 with RC-2 gathered 18 points and circular column improved to 15 points. The best fluidization quality was observed when using Sand Sieve No. 30/60 with grade points of 18 for both cases of rectangular columns and 17 points for circular column.

For circular column, the three sand sieve no. used in the test showed an increase in fluidization quality where Sand Sieve No. 30/60 accumulated 17 points through all the fluidization numbers (3 U_{mf} to 8 U_{mf}) whereas the Sand Sieve No. 10/20 exhibited the poorest fluidization quality with only 5 points. The fluidization quality of the Sand Sieve No. 20/30 was in between these two sand sieve no. Results also showed that the laminar fluidization (3 and 4 U_{mf}) was observed with no circulation of sample and sand bed for Sand Sieve No 10/20. Increasing the fluidization number caused slug formation which was an indication of very poor fluidization quality. For Sand Sieve No. 20/30, the fluidization was improved in which the range of fluidization numbers was between 3U_{mf} to 7 U_{mf}. However, at 8 U_{mf}, the bed formed slugs thus limiting it fluidization capability. The best result was observed when using Sand Sieve No. 30/60. The turbulent fluidization was observed from 4 U_{mf} until 8 U_{mf}. No formation of slugs was observed and the circulation of sample in bed was excellent. From these observations, the general conclusion can be made regarding the effect of sand size on the fluidizing behavior in a circular column. The coarse sand (sand sieve no. 10/20 with its mean size of 0.87 mm) exhibited less fluidization quality compared to smaller mean size sand of sieve no. 20/30 (mean size of 0.67 mm) and 30/60 (mean size of 0.34 mm) respectively. Slug also formed easily when using coarse sand.

For rectangular columns, RC-1 and RC-2, the improvement of the quality of fluidization was seen when using Sand Sieve No 20/30 and 30/60. For Sand Sieve No. 10/20, the quality was poor. However, for all cases, no slug formation was observed at any fluidization numbers. The fluidization was mainly of turbulent in nature and the sample and sand mixed well inside the bed. For both cases of rectangular columns and circular columns, the behavior of the fluidization improved significantly when using sand of smaller mean size. The results on the circular and rectangular columns also pointed out the effect of aspect ratio (bed diameter over bed height) on the formation of slugs.

Sand Sieve No. 30/60 fluidized well and bubbles started to form at or only slightly above minimum fluidization velocity. Bubbles formed when using this sand was smaller than those in large particle (Group D) beds. Reviewed on the nature of each sand group also pointed out that group B (Sand Sieve No. 30/60) was more cohesive as a result of various forms of inter-particle forces. The inter-particle forces include the electrostatic forces and it resulted from the interaction of the absorbed layers of gas with the particle. However, inter-particle forces do not play any role in Group D (Sand Sieve No. 20/30 and 10/20) particle due to their coarse size nature.

Cranfield and Geldart [9] mentioned that the beds of at least 20 cm diameter must be used to ensure three-dimensional behavior. Therefore, considering the current column dimensions, both rectangular columns fall under the two-dimensional column (2D) category whilst the circular column is considered as a three-dimensional (3D). Bubbles in 3D are free from the influence of the walls whereas in 2D column, the front and back bounding walls affects the growth of the bubbles, hence affecting the fluidisation. Describing the flow of bubbles in 2D and 3D columns, it was observed that at lower fluidization number, bubbles travelled in straight lines. The bubbles that originated from the orifice nearest to the wall were affected and unable to coalesce to the adjacent bubbles. As a result, the overall bubble diameter was reduced significantly. This effect was more pronounced in the RC-2 test where the width of the column was only 11.5cm. As the fluidization number was increased higher, all the bubbles formed were observed to moved to the direction away from the wall and travelled to the middle of the bed and coalesces to each other. This behavior was also observed by [10-11].

Results of the fluidization behavior on the RC-2 column (2D column) for Sand Sieve No. 30/60 showed that all the flow was in a turbulent mode (from 3 U_{mf} to 8 U_{mf}). No formation of slug was observed. A part from bubble deterioration due to wall effect, bubble splitting especially in high fluidization number could be the probable caused in maintaining the flow in the turbulent regime. The phenomenon of bubble splitting was described by [12] who stated that bubbles split at higher jet velocity. Bubbles splitting resulted in smaller bubbles and thus better contact between solid and sand. The air distributor had different number of orifices for each reactor column due to its column size. The circular column has 60 orifices in which air passed through it. On the other hand, RC-1 had 48 orifices whilst RC-2 only had 33 orifices. The difference in the number of orifice in each reactor column for the same cross-sectional area of these three beds contributed to a different air velocity inside the bed. The highest velocity was at RC-2 and circular column showed lower air velocity. Therefore, RC-2 exhibited highest air jet velocity, thus resulting in smaller bubbles.

As the bubbles rose to the centre of the bed and subsequently coalesced on their way up to the top of the bed, two big sand vortices were generated in the bed. The first big vortice moved upwards in the direction close to the centre of the bed and then the second vortice moved downwards to the bottom of the bed. These pattern were observed in both cases of 2D and 3D beds though bubbles growth were restricted by the front and back of the column walls in a 2D bed. Nevertheless, the information gained from this study suggested that the wall effect was dominant when using 2D but 3D bed was free from disturbance. The 2D column was better in terms of fluidization behavior due to smaller bubbles formed but in the real combustion operation, no such dimension was ever constructed. Hence, the fluidization quality was in fact affected by the selected column sizes as well as the mean sand sized being used. With respect to the column shape factor, [13] noticed the similarity of solids circulation pattern in the rectangular and circular columns. The statement strongly supported the argument that the column shape does not have any effect on the bubbles and circulation pattern.

4.0 CONCLUSIONS

The fluidization behavior in the fluidized bed can best be categorised into three mode of flow regimes namely laminar, turbulent and slugging. Generally, laminar flow occurred at low fluidization number whereas turbulent regime happened at higher fluidization number. Slugging behavior, however, depended on sand mean diameter or sand physical properties. These three types of flow regimes significantly determined the mixing characteristics of the solid sample and sand. The laminar flow exhibited slow moving bubble; hence, the circulation pattern of sand was poor. Sample was unable to penetrate inside the bed and mostly stayed on top of the bed. Turbulent flow was desirable since the sand and sample can mix together and eventually circulate inside the bed. Slugging flow must be avoided since no mixing and solid and sand circulation inside the bed was very poor.

The quality of fluidization reported in the study of the hydrodynamics of circular and rectangular column was observed to be depended on several factors. Among them were the sand mean size and fluidization number (excess gas velocity). It was shown that large particle of group D (Sand Sieve No. 10/20) provided less resistance to the bed expansion due to its physical properties. Group D particles have bigger bed voidage, less inter-particle force between them. In the case equal height of 1 Dc, in which Sand Sieve No. 10/20 was used, the maximum range of suitable fluidising numbers were 4 U_{mf}. Beyond that region slugging occurs and that determines the onset of slugging for Sand Sieve No. 10/20. In contrast, Sand Sieve No. 20/30 exhibited maximum range of fluidising numbers to 7 U_{mf}, showing that the difference in sand sizes in fact affects the fluidising quality. Sand Sieve No. 30/60 on the other hand showed wider range of fluidising numbers, in which the fluidisation pattern was of laminar mode at 3 U_{mf} and subsequently changed to turbulent fluidisation at higher fluidisation numbers until 8 U_{mf}.

The fluidization quality was affected by the mean sand size being used. The effect of column sizes also contributed to the fluidization behavior in a fluidized bed. Bigger column was required to produce good fluidization behavior and column shape does not have any effect on the fluidization behavior.

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